Impact of US Airline Network Topology on Air Transportation Efficiency

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Abstract— **Much of the current research aimed at reducing the air transportation system's impact on the environment revolves around increasing the aircraft fuel efficiency or improving air traffic management practices. There are, however, many other factors that play a role in determining the system-wide efficiency of air transportation, such as the airline service route network topology characteristics, aircraft fleet mix and resource allocation. This paper investigates the impact of different service route network topology types on transportation efficiency metrics developed by the authors.**

Keywords-network; efficiency; airlines; environment

I. INTRODUCTION

Transforming the national and international Air Transportation Systems (ATS) to meet future travel demand has been the focus of many researchers and decision-makers. This challenge has become further complicated by increased noise and emissions restrictions stemming from growing awareness of the aviation industry's impact on the environment and by increased economic pressure due to volatile fuel prices. Improving individual aircraft efficiencies and air traffic management (ATM) practices have been common approaches to satisfy increasing travel demand while reducing environmental impacts. While it is very important to assess and improve the efficiencies at the level of individual aircraft and ATM procedures, there are many other high-level factors beyond these that determine the system-wide efficiency of air transportation, such as the airline service route network topology, aircraft fleet mix and resource allocation. These factors are extremely large in scope and their complex nature makes analysis as well as subsequent design decisions extremely difficult.

The lack of a universal definition that describes the overall efficiency of the ATS exacerbates the problem. This is mainly due to the distributed control and heterogeneous structure of the ATS composed of multiple stakeholders (e.g., passengers, airlines, airports, etc.) operating under a unique set of objectives, timescales and domains (e.g., economical, operational, and political) [1]. Since each stakeholder has their own set of objectives, they also have their own perception of what "ATS efficiency" means. For example, ATS efficiency for an airline may be based on the economical effectiveness of meeting passenger travel demand. However, from a passenger point of view, efficiency may also be based on required travel time or number of connections, which does not necessarily coincide with an ATS architecture designed for economical effectiveness (e.g., hub-and-spoke type service route network). Further, ATS efficiency defined by the amount of noise or emissions released may contradict the metrics formed for either the passengers or the airlines.

The research reported in this paper describes preliminary steps taken by the authors in analyzing the trade-offs between efficiency metrics from different stakeholder standpoints. More specifically, this paper investigates trade-off studies between passenger-centered efficiency metrics and different types of airline service route network topologies. The remainder of the paper is organized as follows: After a brief literature review on some of the efficiency metrics related to the ATS in Section II, network theory is introduced. Section III describes the efficiency metric that was used as a baseline to compare the performance of the various service network topologies, portrayed in Section IV. Section V summarizes the interim results, followed by key implications in Section VI.

II. BACKGROUND

A. *Literature Review*

In recent years, a significant amount of research towards improving the efficiency of air transportation networks was based on improving individual aircraft performance. Reference [2] is an example of this, employing energy usage and specific energy intensity—largely aircraft-centric measures—as the performance metrics for analyzing the current and historical ATS. Energy usage and specific energy intensity were examined as a function of different types and classes of aircraft. These metrics are primarily influenced by aircraft design decisions, such as propulsion type, passenger load, technological evolution, and the specific mission design requirements. By using energy as part of their metric, the authors implied that improving the fuel efficiency of an aircraft would have a direct impact on the overall air transportation network efficiency. This allowed for the impact of individual aircraft design parameters on the overall efficiency of the air transportation system to be explored. Since passenger load was also taken into account via specific energy intensity, some light was also shed on the effects of fleet operations on transportation efficiency. However, these metrics do not necessarily provide explicit results for changes in specific fleet

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operations or network topology. In addition, there are trade-offs between airline equity and passenger equity, as Manley and Sherry [3] demonstrated.

Instead of individual aircraft metrics, [4] used fleet level metrics to examine how changes in fleet operations affect air transportation network efficiency. Route demand, number of aircraft on route, route distance, passenger load, number of aircraft, and maintenance hours were among various factors used to create an objective function modeling fleet efficiency. These factors were primarily affected by the fleet distribution and allocation of different types and numbers of aircraft to each route. It also presented methods to implement new aircraft technology into the tool to obtain new and ideal fleet distributions, thereby linking aircraft design with fleet efficiency. Again, while changes in the fleet mix were examined and applications to aircraft design were offered, changes in network topology were not formally addressed.

Reference [5] addressed network utilization by examining the cost of establishing routes based on an efficiency metric that examined the trade-off between the wait/fly ratio and route distance ratio. Using airlines as rational agents, the wait/fly ratio and route distance ratio were weighted and the cost and utilization of the ATS were evaluated. While this allowed for the comparison of network properties with network efficiency, the process was not directly related to the aircraft design process, and again network topology was not necessarily an intended design parameter.

Two tools currently under development served as inspiration and background for this paper: The Aviation Environmental Portfolio Management Tool (APMT) [6] and Aviation Integrated Modeling Tool (AIM) [7]. Both of these tools were and are being used in the context of evaluating system benefits, costs, policies, operations, etc. based on a set of inputs specified by the user. The purpose of each tool was to provide the user with options for changing system inputs, parameters, and characteristics in order to achieve an efficiency goal. What set these two tools apart from aircraft-centric research on the topic of efficiency was their use of network architecture and complex layers of objectives as part of the analysis. However, while these tools addressed the fact that small changes in the network architecture could result in large scale differences in ATS performance, no specific measure of ATS efficiency was presented or validated as a proper baseline. This provided the motivational basis and outline for the experimental design in which the network topology was varied in order to achieve an efficiency target, as described in subsequent sections.

B. Introduction to Network Theory

Network Theory has produced powerful results from multiple domains (e.g., physics, information, social science, biology) in recent years concerning how real-world networks are structured. Some researchers have applied the analysis techniques developed in the network theory community to explore the structure of the ATS. Guimera, et al. analyzed the worldwide air transportation network topology and computed measures which characterized the relative importance of cities and airports [8]. Further, Bonnefoy and Hansman used the weighted degree distribution for light jet operations to understand the capability of airports to attract the use of very light jets [9]. A significant body of works exists in the related domain of operations research on the design of optimal networks for particular instances and applications (e.g., schedule for an airline). However, these approaches generally do not pursue how the underlying network topology influences the characteristics of the ATS as a whole, the interplay between networks that reside in different domains, or the role these structures play in future designs. Applying network theory not only as an analysis tool but also for designing the future ATS has been a continuing topic for our work [10, 11]. In particular, this paper examines the trade-offs between performance and risk of different network topologies for to the airline service route network is investigated in Section IV and V, which may be applied towards future ATS designs.

III. TRANSPORTATION EFFICIENCY FORMULATION AND ANALYSIS OF THE HISTORICAL ATS

In systems with multiple stakeholders such as the ATS, objectives between the stakeholders may conflict. As a result, metrics may favor one stakeholder over another in representing how efficient the system is. Further, stakeholders seek to optimize their operation with regard to their own objectives. For instance, airlines use the hub-and-spoke system to reduce costs. In particular, hubs allow airlines to aggregate passenger origins to more efficiently transport them to their destinations. While this may be ‘efficient’ for the airlines from an economic standpoint, it may be detrimental to the passengers in that they may need to travel extra distance to their destination, or for the regulators that prefers to keep the density of operations low to maintain safety.

As an initial step to investigate the potential trade-offs between efficiency from various stakeholders’ standpoint, passenger travel distance efficiency was created to determine the impact of airline service route network topology on travel distance for passengers, shown below.

$$\tau = \frac{d_{ij}}{d_{tot}} \tag{1}$$

d_{ij} is the distance between the passenger's origin and destination where d_{tot} is the total distance traveled by the passenger, which includes connections, if any. In this formulation, τ is less than or equal to one, where $\tau = 1$ for direct flights.

Using this formulation, τ was calculated for every itinerary in the DB1B datasets from 1993 to 2007. The DB1B is a 10% sample of all itineraries flown and reports the actual routing of passengers. Calculating τ for each passenger allowed the average efficiency to be computed. Efficiency varied from year to year, as shown in Figure 1, but averaged quite high at 92.7% for the years investigated. To examine some of the potential effect of airline’s hub-and-spoke structure, the average efficiency was also computed for indirect flights only. As expected, these efficiencies (also shown in Figure 1) were lower but only slightly, averaging 88.5% for the 15-year period.

According to the data, the average passenger flying on an itinerary with at least one connection traveled 12.5% farther than he/she would have on a direct flight. Given that the average trip length (from origin to destination) in 2007 was 917 km (570 mi), the average traveler flew 1036 km (644 mi) instead. Note that this is only an indication of how much farther a traveler was made to travel and does not take into consideration time or monetary cost to the traveler.

As different airlines route passengers differently according their service network, it stands to reason that the efficiency of one airline may differ from another. To explore this, we selected two types of airlines: traditional hub-and-spoke carriers (Delta and American Airlines) and an airline with more point-to-point operations (Southwest Airlines). Using the same method for calculating τ for all flights, time histories of average τ were created

Delta had slightly lower efficiencies, as shown in Table 2, but followed the same general trend as the overall ATS. Southwest Airlines, with its focus on point-to-point service had nearly equivalent efficiencies (to the overall ATS) over the 1993–2007 timeframe. However, Southwest was also growing its operations during the first half of that period and still operated many of their flights from a few major airports. As their service area grew, more direct flights were added, resulting in higher τ for travelers since 1999, as shown in Figure 2. Considering only itineraries from 2001 to 2007, τ of the average passenger flying on Southwest was 2% higher than the national average (see Table 1).

TABLE 1. PASSENGER TRAVEL DISTANCE EFFICIENCY ACCORDING TO AIRLINE

Airline	Average Passenger Excess Travel Ratio (τ)	
	All Flights	Indirect Flights
All Airlines	92.7%	88.5%
Delta Airlines	90.8%	87.4%
American Airlines	92.9%	88.9%
Southwest Airlines	93.2%	88.6%
Southwest Airlines (2001–2007)	94.8%	89.4%

In addition to Delta and Southwest, flights on American Airlines were also analyzed. This allowed service network topology and carrier operations to be compared with respect to τ. In this case, Delta represented an airline with a hub-and-spoke structure which also participated in a large degree of code-sharing (many "Delta passengers" traveled on other carriers in the course of their trip). Similarly, American had a largely hub-and-spoke service topology, but had very little code-sharing. Southwest's network, however, was comprised of weaker hubs and had virtually no code-sharing.

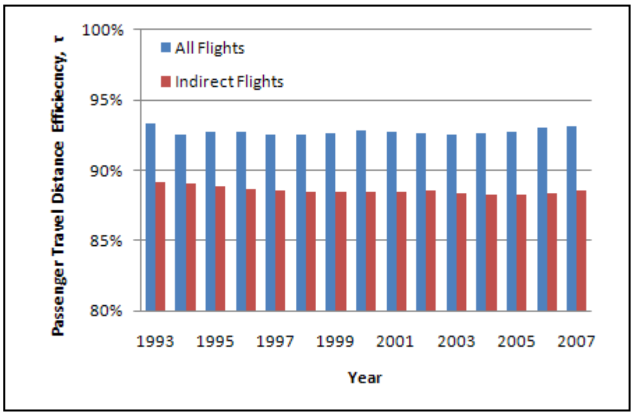

Figure 1: Variation in average τ over time for all airlines.

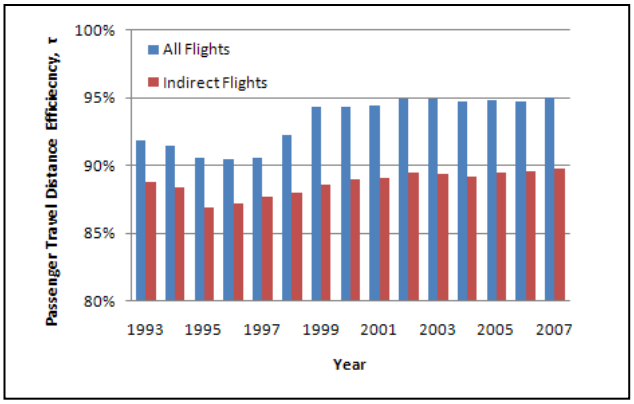

Figure 2: Variation in average τ over time for Southwest Airlines.

IV. NETWORK TOPOLOGY TRADE-OFF STUDY DESCRIPTION

A. *Overview*

The previous section investigated the historical trends of passenger travel distance efficiency for the ATS and selected airlines. In this section, the correlation between airline service route network configurations and passenger centered ATS efficiency is explored. The airline service route network topology examined here is on an annual scale and scheduling of actual flights is not considered. In another words, links in the service route network are simply paths which allow transporting of passenger from their origin to destination airports (nodes) for a particular annual demand. Further, all the airlines service routes are aggregated into one single network unless otherwise noted.

Different types of networks are generated under the topology generator discussed in the following section. For each topology type studied, the passenger travel distance efficiency (τ) as well as the number of connections required to transport the passenger on the shortest routes are calculated. Data on historical passenger demand and airport operations are extracted from the 2005 DB1B Survey and T-100 Domestic Segment data respectively, both available from the Bureau of Transportation Statistics [12]. The number of nodes in the network is kept constant at 304, representing the airports only in the continental US.

B. *Network Topology Generator*

Currently, random and scale-free networks are the most discussed types of network topology used for analysis. Scale-free networks are similar to the hub-and-spoke networks of the ATS where few nodes with high degree (i.e., number of links) maintain the connectivity throughout the network. Similar structure is also seen in protein networks, social networks and the World Wide Web [13]. The prime benefits of this structure are that all nodes are connected via relatively few links, and new nodes can be easily integrated as long as the hub nodes are functional. On the other hand, the main drawback of a scale-free network is that as the hub nodes become larger, the risk of a devastating single point of failure increases significantly. Scale-free networks can be constructed using the Barabási-Albert (BA) model [13] which runs under the precept of a preferential attachment behavior where nodes with higher importance are granted a higher probability to attain a new link. In the BA model, importance of a node is valued by its local degree compared to the total degree of the network. In another words, the probability of node *A* linking with any other node *B* is

$$P_{connect}\ (A,B) = \frac{k_A}{\sum_{i=1}^{j} k_i} \qquad (2)$$

where j is the total number of nodes in the network and k is nodal degree. For random networks, links between nodes are constructed based on a uniform probability distribution function which remains constant for all node pairs that may form a link. While random networks require more links for equal shortest-path connectivity compared to a scale-free, the single point of failure risk is much lower since all nodes are almost equally important in terms of the number of connections [13].

The Network Topology Generator (NTG) constructs a network with varying mix ratio of scale-free and random characteristics, based on the user input. The NTG algorithm first generates two networks, random and scale-free (via uniform distribution and (2), respectively), with equal total number of links for the same node set. The NTG then arbitrarily selects links from the scale-free and random network and places it in the final network; the number of links chosen from either the scale-free or random network depends on the user input mix ratio mentioned earlier. For example, if the mixture ratio was 80% scale free, the NTG will chose 80% of the final links from the scale-free network generated in the initial step, while extracting the remainder 20% from the random network. Networks of different scale-free and random topology mix ratios will be examined for the impact on passenger travel distance efficiency and number of connections required to fulfill demand.

V. RESULTS

A. *Passenger centered Efficiency*

Topologies with six scale-free / random mix ratios and four different network densities were created for this study. Network density is simply the ratio between the total network number of links in the network and number of possible links that can exist in a particular network size. Using the 2005 ATS network with 304 nodes and 6% density (2612 links) as a baseline, networks with 12%, 3% and 1% density were considered.

Figure 3 displays the τ for each topology type and Figures 4 through 7 show the ratio for number of connections required to fulfill the annual passenger travel demand. Each column shows the different network mix ratios. For example, “BA80” means 80% of the links came from the BA (i.e. scale-free) logic, while the remaining 20% is from the random network logic. Not all passengers can be transported from their origin and destination demand by available routes for the networks generated by the NTG. This is due to non-connected ‘island’ clusters that occasionally form in random networks with low density, but as shown in Table 2, only a small portion of the passengers in the 1% density topology cannot be transported. In addition, results displayed in Figure 3-7 are an average value over 10 runs, and the fluctuation between each run is relatively small (<5% on average).

As expected, the travel distance efficiency increases for topologies with higher density and more scale-free characteristics (Figure 3). However, the difference in τ was considerably small between the higher and lower density networks. For example, τ in a network with 1% density was 37% less compared to a 12% density network under the BA100 mix ratio. In a network with 304 nodes, this 10% difference in density is equivalent to approximately 5000 links. Since all demand is still satisfied (as shown in Table 2) the service route network with 1% density was able to transport the same amount of demand with about 5000 fewer links, in exchange for lower travel distance efficiency. Further analysis between degree and travel distance efficiency may be a useful study for future ATS transformation efforts if links are considered as resources in constructing a network. However, higher network density significantly decreases the minimum number of connections required on the shortest distance route as it can be seen in Figures 4–7.

TABLE 2. PERCENT OF PASSENGER DEMAND THAT CANNOT BE SERVED

Network Density	**NTG Topology Mix Ratio**					
	BA 100	***BA 80***	***BA 60***	***BA 40***	***BA 20***	***BA 0***
12%	0%	0%	0%	0%	0%	0%
6%	0%	0%	0%	0%	0%	0%
3%	0%	0%	0%	0%	0%	0%
1%	0%	0.7%	1.4%	0.5%	1.3%	2.5%

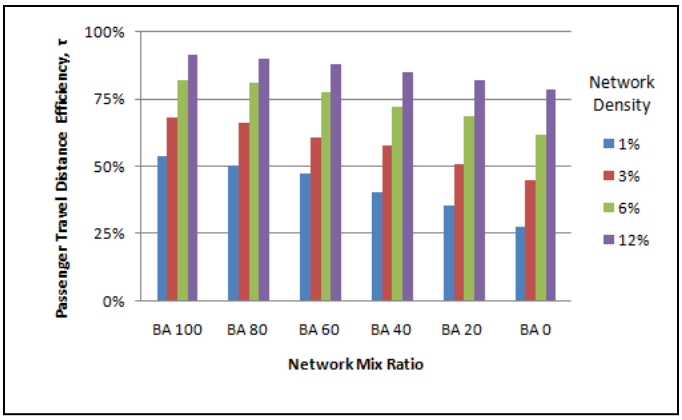

Figure 3. Passenger travel distance efficiency for different network mix ratio and network density.

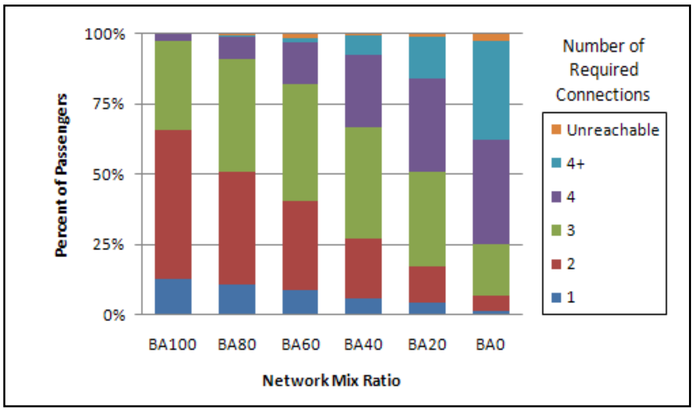

Figure 4. Number of required connections for network with 1% density.

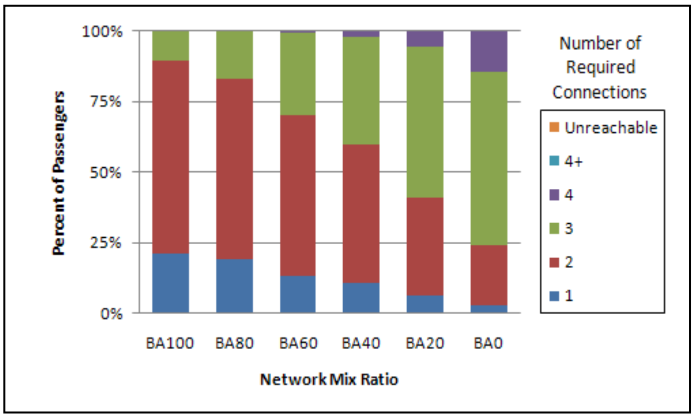

Figure 5. Number of required connections for network with 3% density.

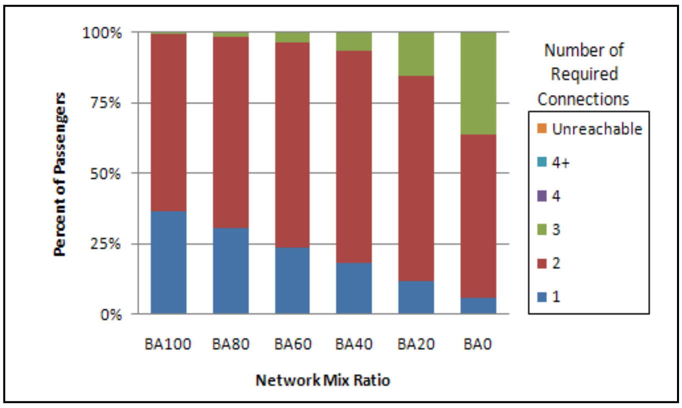

Figure 6. Number of required connections for network with 6% density.

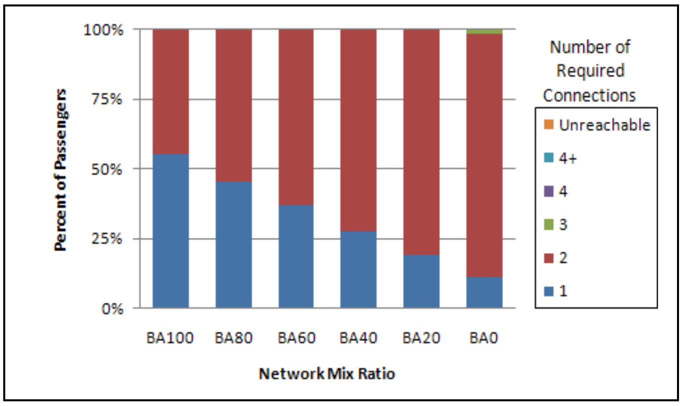

Figure 7. Number of required connections for network with 12% density.

B. Network Topology Robustness

Beyond the passenger centered efficiency discussed in the previous section, metrics regarding airline network robustness were also investigated. However, one cannot speak generally about robustness; instead, a class of possible disturbances must be specified in order to measure or estimate a particular robustness characteristic of the system. In terms of networks, there are two general types of “attack” that may cause disturbances: targeted and random. These attacks disable the function of a node (airport) and either temporarily or permanently remove it from the entire network, along with any associated links. Random attacks are arbitrary failures that can occur to any nodes within the network under certain probability; they usually represent incidents such as weather, accidents, and aircraft malfunctions. Targeted attacks, on the other hand, are failure of specific nodes which are usually due to an artificial cause. In the real world, targeted attacks may occur as terrorism, strike, or war-related issues.

Robustness of each network topology configuration is examined by measuring the degradation in τ and percent of passengers unable to travel after certain nodes are removed, mimicking targeted and random attacks. For targeted attacks, nodes with the highest degree are removed while for the random attack, nodes are removed randomly for the network. For each attack type on the different network configurations, five, ten and fifteen nodes were removed to observe how increasing number of failed nodes degrade the overall network performance. Tables 3 and 4 display the amount of performance degradation of the networks after the disruptions in terms of τ and percent of passengers unable to travel, respectively.

While both scale-free and random networks are fairly resistant towards random attacks, it can be observed that scale-free networks are extremely fragile towards targeted attacks until a certain network density is attained. Further, although the majority of passengers were unable to travel after targeted attacks on networks that exhibit the slightest scale-free characteristics, a fully random network is able to maintain routes to travel approximately 90% of the passengers.

TABLE 3. PRECENT REDUCTION IN PASSENGER TRAVEL DISTANCE EFFICIENCY (τ) AFTER DISRUPTION

Network Density	Disruption Type	Disabled Nodes	BA100	BA 60	BA40	BA0
3% (1306 links)	Random	5	0.04	0.51	0.22	0.28
		10	0.16	0.24	0.69	0.45
		15	0.02	0.70	0.72	0.65
	Targeted	5	22.35	16.45	14.32	2.17
		10	22.35	16.45	14.32	2.17
		15	28.24	20.79	17.63	3.04
6% (2612 links)	Random	5	0.09	0.16	0.00	0.16
		10	0.43	0.23	0.27	0.81
		15	0.34	0.85	0.61	0.87
	Targeted	5	3.57	4.16	2.83	1.18
		10	8.15	8.51	6.93	1.93
		15	14.49	14.23	11.39	2.77
12% (5224 links)	Random	5	0.01	0.11	0.39	0.25
		10	0.19	0.25	0.34	0.41
		15	0.18	0.48	0.61	0.61
	Targeted	5	1.52	1.52	1.65	0.46
		10	2.94	3.24	2.97	0.89
		15	5.10	4.90	4.75	1.29

TABLE 4. PERCENT OF DEMAND THAT CANNOT BE SERVED AFTER DISRUPTION

Network Density	Disruption Type	Disabled Nodes	BA100	BA 60	BA40	BA0
3% (1306 links)	Random	5	3.04	3.38	2.77	4.19
		10	5.11	5.87	8.24	5.65
		15	6.06	13.72	9.66	7.34
	Targeted	5	55.80	54.07	55.54	8.79
		10	55.80	54.07	55.54	8.79
		15	67.49	67.81	64.88	11.64
6% (2612 links)	Random	5	1.78	2.42	3.44	4.19
		10	6.75	4.65	5.40	7.14
		15	6.99	9.76	11.38	11.78
	Targeted	5	26.02	28.09	22.69	5.16
		10	46.82	47.63	45.50	8.84
		15	64.20	64.88	61.83	12.75
12% (5224 links)	Random	5	2.59	1.83	6.15	4.28
		10	4.71	5.04	7.21	8.55
		15	9.37	11.52	9.11	7.74
	Targeted	5	23.58	21.91	20.00	1.94
		10	41.16	38.46	37.83	5.10
		15	53.80	53.70	51.08	8.36

In summary, what is meant by a “favorable” network configuration for the ATS is quite different depending on the focus of the efficiency metric. From the perspective of τ and number of connection required to transport passengers under historical patterns, a network that shows strong scale-free characteristics seems more suitable. However, a random configuration seems to be more ideal from a robustness standpoint, since they are more resistant to both targeted and random attacks compared to a scale-free type topology.

VI. CONCLUSION AND FUTURE WORK

Research reported in this paper provided an initial investigation on how system configurations for large scale systems like the ATS may differ depending on stakeholder viewpoints. Specifically, a rudimentary trade-off among different airline service network configuration was examined for both efficiency in processing travel demand and resistance to various failure modes. Current results presented throughout the paper show that the favorable network configurations may lie on opposite extremes depending on the different objectives examined. We do recognize that the control of the actual service route network structure is distributed among the various airlines; there is no central route-allocating architect. However, the results reported here provide quantitative bounds on the efficiency and robustness of different network configurations that could serve as targets for system transformation. Given these targets, policymaking bodies, as well as airline enterprises, can use the influence factors they do control to drive overall system behavior towards these preferred network configurations. Before further effort in ATS transformation is commenced, objectives need to be prioritized in order to clarify the ideal configuration of the future ATS.

Work reported in this paper describes only the initial investigation of ATS architecture trade-offs, and there is much more work to be done. The first step is to extensively review and construct efficiency metrics that can represent how well a particular stakeholder's objective are met under various architecture configurations. The study on τ, number of required connections and disruption resistance studied in this paper mainly involve the passenger, airlines and regulators but the actual ATS involves many more stakeholders that need to be considered such as airports, air traffic controllers and so forth. Second is to construct a series of analysis method that can cut across multiple timescales since each stakeholder's objective may reside under different timescales. For example, airports often use arrival and departure operations that can be processed per minute or hour. However, for stakeholders that emphasize long-term ATS capabilities such as sustainability, trade-offs cannot be made under the current approach. In the short term, we plan on expanding the boundaries of this study to aircraft and fleet mix design, which would also incorporate efficiency on fuel use towards different network configuration options.

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